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A MODEL TO PREDICT TRANSIENT DIELECTRIC-CHARGING EFFECTS IN RF MEMS CAPACITIVE SWITCHES

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14. ABSTRACT
Wafer-level micro-encapsulation is an innovative, low-cost, wafer-level packaging methods for encapsulating RF MEMS switches. This zero-level packaging technique has demonstrated 0.04 dB package insertion loss at 35 GHz. This article overviews the processes, measurements, and testing methods used for determining the integrity and performance of individual encapsulated RF MEMS packages.

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A Model to Predict Transient Dielectric-Charging Effects in RF MEMS Capacitive Switches

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Abstract—For the state-of-the-art RF MEMS capacitive switch, a model was constructed to predict the amount of charge injected into the dielectric and the corresponding shift in actuation voltage. The model was verified against the transient actuation-voltage shift under different control waveforms. Therefore, for RF MEMS capacitive switches that fail mainly due to dielectric charging, the present model can be used to design control waveforms that can either prolong lifetime or accelerate failure.

I. INTRODUCTION

Despite the near-ideal performance of RF MEMS capacitive switches, their lifetime is limited by dielectric-charging effects [1]. To date, dielectric-charging effects in RF MEMS devices have been studied by different groups [2]-[4] and a charging model was experimentally extracted [4]. This paper reports the model prediction of charging under control waveforms of different voltages, frequencies, and duty factors.

II. EXPERIMENTAL

Fig. 1 illustrates a state-of-the-art metal-dielectric-metal RF MEMS capacitive switch fabricated on glass substrate. A transient dielectric-charging model was extracted from the measured charging/discharging currents of the traps in the switching dielectric for the switch in Fig. 1. Detailed switch design parameters, charging model equations, and model parameters were reported in [4]. Accelerated lifetime tests for the switches were performed on a time-domain switch characterization setup [1]. A 6 GHz, 10 dBm sinusoidal signal was applied to the switch input port together with the control waveform. The RF output was sensed by using a Narda 26.5 GHz diode detector. Both the control and output waveforms were monitored by using an oscilloscope. The switch was stressed by applying a stressing waveform (square or dual-pulse waveform) for different time periods. A saw-tooth control wave of 0 to -30 V was applied to the switch to sense the pre-stress and post-stress actuation voltages. This way, the actuation-voltage shift for each stressing time period can be determined.

III. RESULTS AND DISCUSSION

Fig. 2 illustrates a charging curve that starts from the origin and ends in saturation (State S), which is followed by a discharging curve that falls exponentially. Both curves were calculated from the charging model parameters [4]. During real switch operation under a square control wave, the charging state at the beginning of each operating cycle can be somewhere between empty and full, such as State A on the charging curve. After the switch is turned on, the charging state moves higher to State B during the on time of the switch. After the switch is turned off, the dielectric starts to discharge from State C on the discharging curve, which is mapped from State B of the charging curve. After certain off time, the dielectric is discharged to State D, which is then mapped back

to State E on the charging curve to start the next operating cycle. Thus, the net effect of one operating cycle is to move the charging state from A to E. The charging/discharging model repeats in such a ratchet fashion until the desired number of cycles has been operated.

Using the above-described calculation routine, charge injection and hence actuation-voltage shift under different stressing frequencies, duty factors, and voltages were calculated and compared with the measured data (Fig. 3, 4, 5). Fig. 3 shows that increasing the duty factor accelerates dielectric charging and actuation-voltage shift at all measurement frequencies. Moreover, actuation-voltage shift depends strongly on the total stress time instead of the number of operating cycles. Notice that in Fig. 3 the total number of cycles, (a) 2000, (b) 20000, and (c) 200000, at the three frequencies correspond to the same total stress time of 200 s. Hence, within the frequency range of 10 to 1000 Hz, charge injection has no obvious dependence on the stress frequency as further illustrated in Fig. 4. This is consistent with the experimental results in [2]. Both modeled and measured data shown in Fig. 5 suggests that increasing the peak voltage accelerates dielectric charging hence actuation-voltage shift. Since the peak voltage affects steady-state charge densities but not charging/discharging time constants [4], similar voltage acceleration can be expected for other frequencies and duty factors.

A dual-pulse waveform has been proposed [1] to minimize charging. The waveform comprises a short high-voltage pulse to quickly pull down the membrane and a low-voltage pulse to hold down the membrane for the remaining on time. As illustrated in Fig. 6(a), the dual pulse used in our experiment is a 100 Hz, 50% duty factor ($t_{ON} = t_{OFF} = 5$ ms) signal. The pull-down pulse width (t_P) was varied as a parameter. Comparing with a 0 to -30 V square wave, the dual-pulse waveforms minimized dielectric charging as expected. The present model can predict dielectric charging under such dual-pulse waveforms as shown in Fig. 6(b).

IV. CONCLUSION

A transient charging model was developed and used to predict the actuation-voltage shift of RF MEMS capacitive switches under accelerated lifetime test conditions. Both modeled and measured data shows that, charging can be accelerated by duty factor and peak voltage instead of frequency of the control waveform. Therefore, the model can be used to design switch control waveforms to minimize the charging effects (prolong lifetime) or to accelerate failure.

REFERENCES

[1] C. Goldsmith, et al., *IEEE MTT-S IMS Dig.*, pp. 227, 2001.
[2] W. M. van Spengen, et al., *IEEE IEDM Dig.*, pp. 901, 2002.
[3] J. R. Reid, et al., *Electron. Lett.*, pp. 1544, 2002.
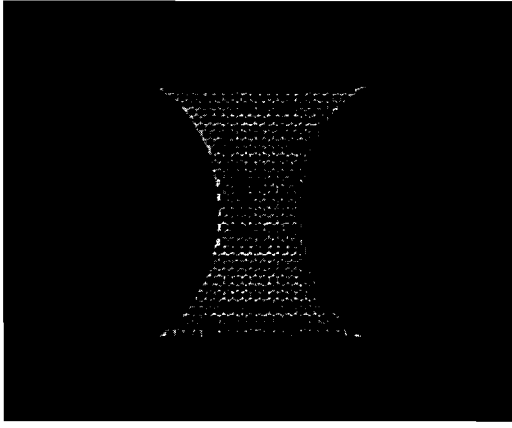[4] X. Yuan, et al., *IEEE MTT-S IMS Dig.*, 2005.

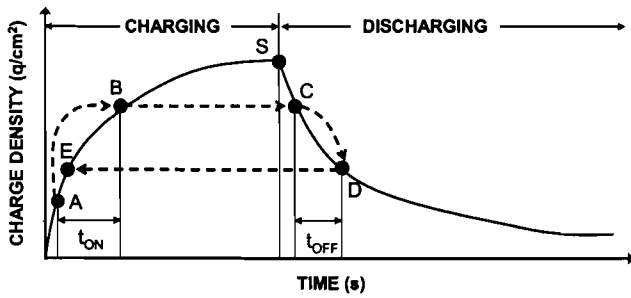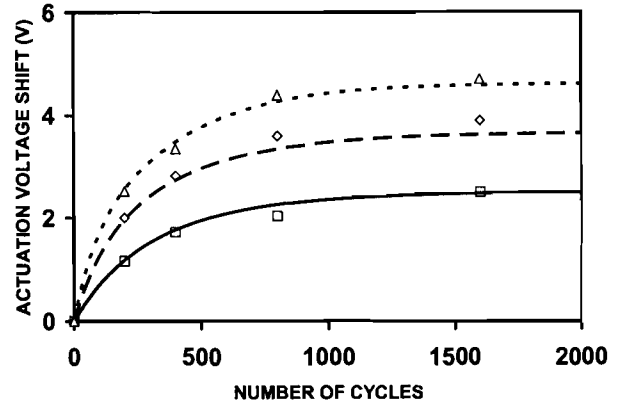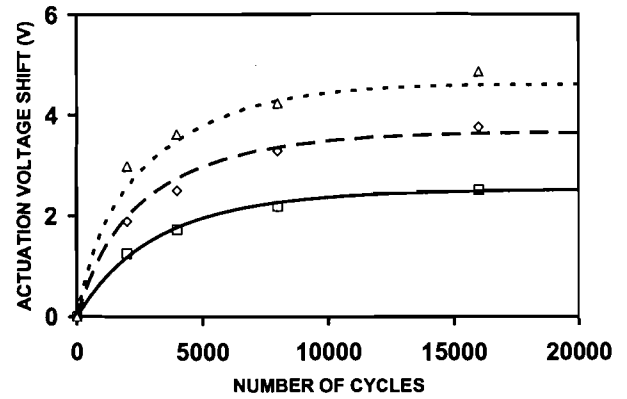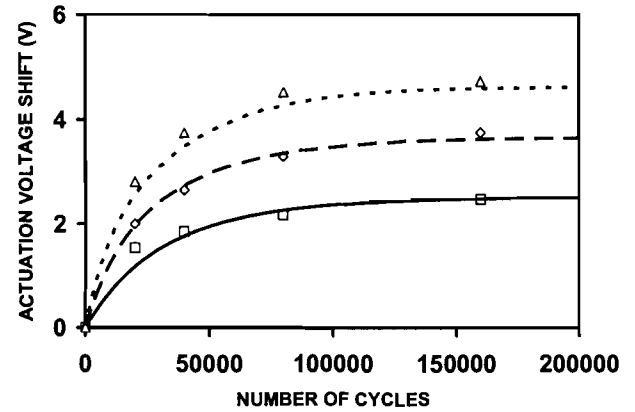Fig. 1. Top view of a state-of-the-art RF MEMS capacitive switch.

Fig. 2. Charging calculation under a square control wave. t_{ON} and t_{OFF} are the on and off times of the switch. After one operating cycle, charge density increases from the initial state A to the end state E.

(a)

(b)

(c)

Fig. 3. Actuation-voltage shift as a function of operating cycles. The stress signal is a 0 to −30 V square wave at (a) 10, (b) 100 and (c) 1000 Hz. Modeled actuation-voltage shifts are for (—) 25%, (- - -) 50%, and (· · ·) 75% duty factors. Similarly, measured actuation-voltage shifts are for (□) 25%, (◊) 50%, and (Δ) 75% duty factors. Stress times (20, 40, 80, and 160 s) were the same for all three frequencies. Both modeled and measured data show that actuation-voltage shift is accelerated by duty factor, but not by frequency.
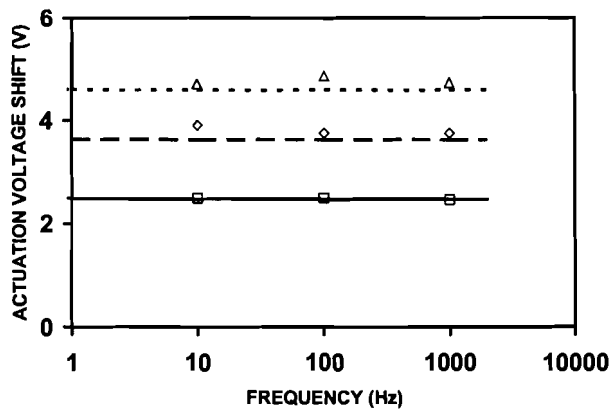
Fig. 4. Actuation-voltage shift as a function of stress signal frequency. The stress signal is a 0 to −30 V, 160 s long square wave. Modeled actuation voltage shifts are for (—) 25%, (- - -) 50%, and (· · ·) 75% duty factors at all frequencies. Measured actuation voltage shifts are for (□) 25%, (◊) 50%, and (△) 75% duty factors at 10, 100, and 1000 Hz. Both modeled and measured data show little frequency dependence.
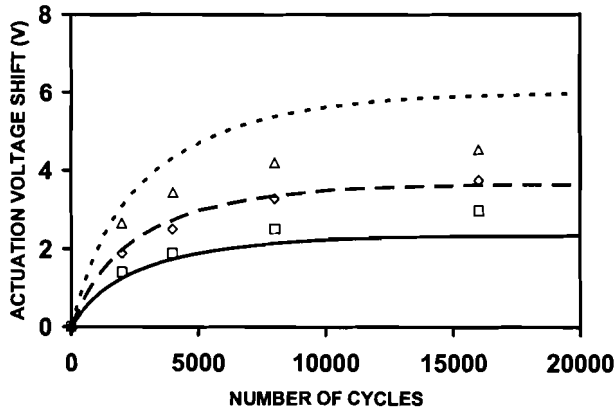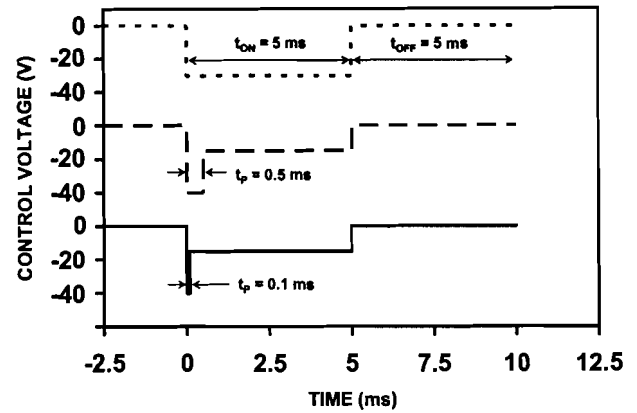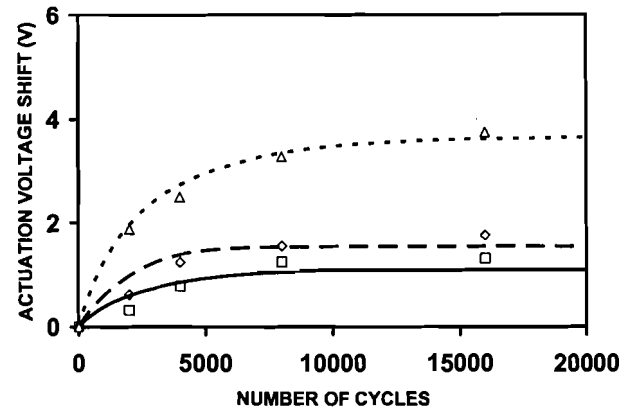

Fig. 5. Actuation-voltage shift as a function of operating cycles and stress voltages under a 100 Hz, 50% duty factor square wave. Modeled actuation-voltage shifts are for (—) −25 V, (- - -) −30 V, and (· · ·) −35 V square-wave peak voltages. Measured actuation-voltage shifts are for (□) −25 V, (◊) −30 V, and (△) −35 V peak voltages. Both modeled and measured data show that charge injection is accelerated by increasing the peak voltage.

(a)

(b)

Fig. 6. (a) Illustration of (—) dual pulse with t_P = 0.1 ms, (- - -) dual pulse with t_P = 0.5 ms, and (· · ·) 0 to -30 V square wave. The stress waveform frequency is 100 Hz. Both square wave and dual-pulse waveforms have 50% duty factor. For the dual-pulse waveforms, pull-down voltage is -40 V and hold-down voltage is -15 V. (b) Actuation-voltage shift as a function of operating cycles. Modeled actuation-voltage shifts are for (—) dual pulse with t_P = 0.1 ms, (- - -) dual pulse with t_P = 0.5 ms, and (· · ·) 0 to -30 V square wave. Measured actuation-voltage shifts are for (□) dual pulse with t_P = 0.1 ms, (◊) dual pulse with t_P = 0.5 ms, and (△) 0 to -30 V square wave. Charge injection is minimized by using the dual-pulse waveforms instead of the square wave.